Interdependent superconducting networks

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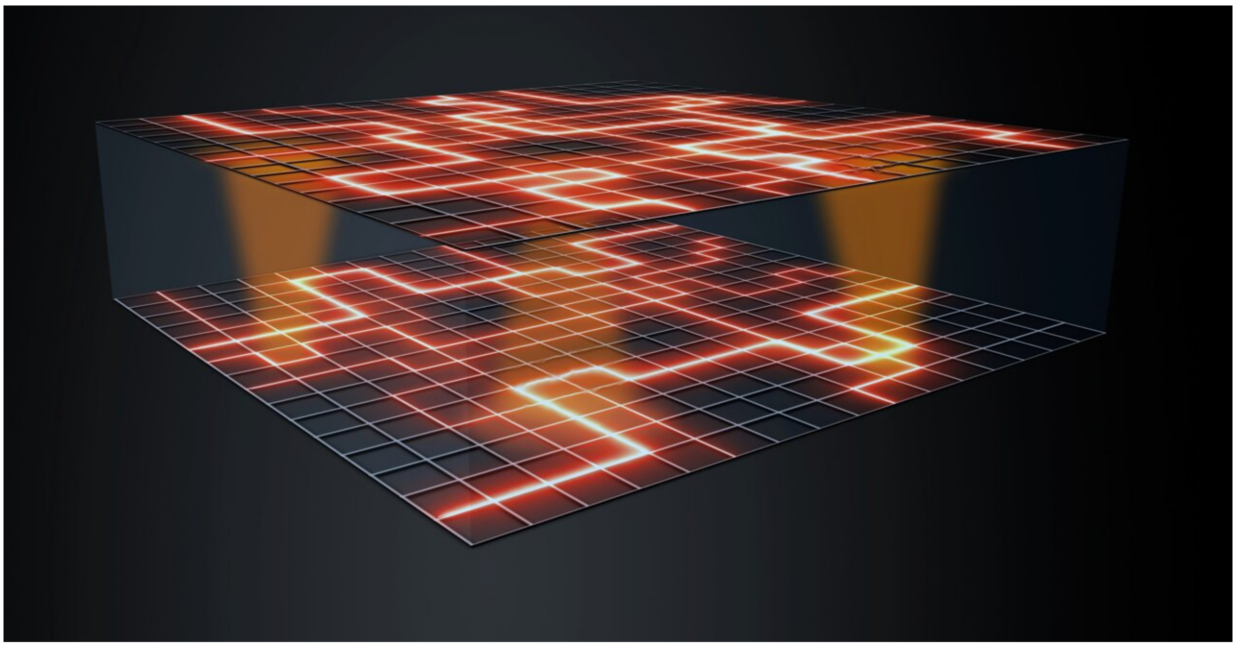

Two network layers, characterized by intra-network connectivity interactions (electric conductivity), are interdependent via dependency interactions (thermal heating) denoted by the red beams. Credit: Figure created by Shahar Melion inspired by a figure by Maya Zakai

In 2010 Prof. Shlomo Havlin and collaborators published an article in the journal *Nature* proposing that the abrupt electricity failure causing the famous 2003 Italy blackout was a consequence of the inter-dependency of two networks. According to Havlin's theory the dependency between the power network and its communication system led to cascading failures and abrupt collapse. Havlin's seminal work ignited a new field in statistical physics known as "network of networks" or "interdependent networks" and paved the way for understanding and predicting the effects of the interaction between networks.

The main novelty of Havlin's model is the existence of two types of links that represent two qualitatively different kinds of interactions. Within networks, links between nodes describe connectivity such as electric power or communication connections. Between networks, on the other hand, links describe dependency relationships in which the functionality of a node in one network depends on the functionality of a node in the other. The communication hubs need electricity and the electric power stations depend on communication control. This dependency leads to a cascading effect in which failure of a single node in one of the networks could lead to an abrupt breakdown of both networks.

Over the past decade or so since, Havlin, from the Department of Physics at Bar-Ilan University in Israel, and others have applied this concept to a variety of abstract systems, such as the internet, road traffic, the economy, infrastructure, and more. But being a theorist, Havlin was unable to manifest the hypothesis on real experimental physical systems and thus the theory couldn't be confirmed in controlled experiments, nor could it be implemented for device-type applications.

Recently, Havlin joined forces with his colleague, Prof. Aviad Frydman, an experimentalist in the Physics department at Bar-Ilan who specializes in electrical properties of disordered systems, in particular superconductors. Superconductivity is a phenomenon observed in certain metals where electric resistance vanishes when the system is cooled down below a critical temperature.

Inspired by Havlin's theory, Frydman's group developed a controlled system of interdependent superconducting networks, a physical analogy to the interdependent networks involved in the Italy blackout. The two superconducting networks are separated by a layer which is an electric insulator but enables transfer of heat between the networks, thus creating a system of two types of interactions. Within each layer, the electric currents represent connectivity links while the heat flowing between networks represents dependency links since it can disrupt the superconductivity segments.

Havlin's and Frydman's collaborative groups included lab manager Dr. Ira Volotsenko and three graduate students, Dr. Ivan Bonamassa, Bnaya Gross and Maayan Laav.

The research conducted by the two groups, published today, May 1, in the journal *Nature Physics*, shows that while separate, uncoupled networks exhibit a smooth, continuous transition between a superconductor and a normal metal as temperature is increased, coupled systems show an abrupt, discontinuous transition, as predicted by the theory. This is attributed to the fact that the current flowing in a normal segment of one layer causes a superposed segment in the other layer to become hotter, and hence, lose its superconductivity. This thermal feedback process between the layers continues in a self-propagating fashion (i.e., cascading back and forth between the layers) and eventually results in a spontaneous propagating avalanche of junctions entering the metallic phase.

The breakthrough study establishes the first physics laboratory benchmark for the manifestation of the theory of interdependent networks, enabling experimental studies to control and to further develop the multiscale phenomena of complex interdependent materials.

This research has vast significance in several disciplines, including basic physics, materials science and device applications. In basic physics, the scientific impact is in the discovery of new physics phenomena related to phase transitions. The results demonstrate that phase transitions governed by a single interaction type, extensively studied for over 100 years, are just a limiting case of a much richer, general phenomena governed by several types of interactions.

The results may also lead to the establishment of a new field of network metamaterials based on coupled layers with different inter-layer interactions exhibiting novel physics phenomena. The research also indicates that the abrupt breakdown of a network system may be a desirable phenomenon. If harnessed, it can be applied toward engineering self-healing systems or to devise high-sensitive switchers or sensors, for example, for single-photon detection.

While network science originated from physics in 2000, its subsequent development and applications have surprisingly not benefitted physics, but almost all other scientific and technological fields. The present study reconnects network science and physics. It is the first to demonstrate that novel concepts developed by network science can significantly benefit physics while discovering novel physical processes, such as new types of phase transitions, when studying interdependent physical systems.

More information: Ivan Bonamassa et al., Interdependent superconducting networks, *Nature Physics* (2023). DOI: 10.1038/s41567-023-02029-z , www.nature.com/articles/s41567-023-02029-z

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